

Estimating Sediment Budget at a River Basin Scale Using a Process-Based Distributed Modelling Approach

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Received: 28 January 2014 / Accepted: 16 June 2014 /
Published online: 25 June 2014
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Abstract The paper presents a process-based distributed modelling approach for estimating sediment budget at a river basin scale with partitions of suspended and bed loads by simulating sediment loads and their interactions. In this approach, a river basin is represented by hillslopes and a network of channels. Hillslopes are divided into an array of homogeneous grid cells for modelling surface runoff and suspended sediments. Channels are defined by incorporating flow hydraulic properties into the respective hillslope grids as sub-grid attributes for modelling both suspended and bed loads. Suspended sediment transport is modelled using one dimensional kinematic wave approximation of Saint-Venant's principles of conservation of mass and momentum. Transport capacity of runoff or streamflow is used to set the limit of suspended sediment transport rate. Bed load in channels is estimated based on the instantaneous water and hydraulic parameters. Fractional interchange between suspended load and bed load is then back calculated. The performance of the model was evaluated through a case study application in a large river basin in Japan. The model satisfactorily calculated the sediment transport and total sediment budget in the basin. The simulated bed load was found to be reasonable and consistent with the water flow and suspended sediment flux. The results showed the bed load can be expressed as a linear function of the suspended load. The fractions of different sediment loads also exhibit linear relationships with water discharge for the rising and recession limbs of the flood hydrographs. The case study has demonstrated that the process-based distributed modelling approach can efficiently describe the basin-scale sediment budgets with due consideration of the suspended and bed loads and their interactions in the hillslopes and channels.

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Keywords Process-based hydrological model · Sediment budget · Sediment dynamics · Suspended load and bed load interactions · Abukuma River basin

1 Introduction

Sediment dynamics are one of the key controlling factors for sustainable natural resource management. Sediment quality and quantity directly influence many environmental aspects such as water quality, navigation, agriculture, forestry, fish habitat (Owens 2005; Bhattarai and Dutta 2007; Alam & Dutta 2012). Understanding the sediment loads and their interactions provide a useful insight for design, management and maintenance of many applications in various fields e.g., infrastructure design, channel stability, reservoir sedimentation, soil erosion, navigation, water quality, agriculture and forestry (Stott and Mount 2004; Walling and Collins 2008; Raven et al. 2010). Process-based and distributed modelling of sediment dynamics at a basin scale is highly desirable for analysing sediment loads and budgets, since sediment dynamics are (1) influenced by a number of basin scale processes (e.g., overbank flow, ground water and river flow, soil erosion, sediment transport and deposition); (2) varied both spatially and temporally; and (3) derived by hydrological events (Owens 2005).

In a river basin, hillslope sediment dynamics are mainly determined by topography and land use patterns, whereas, in-stream sediment dynamics are mostly influenced by channel flow dynamics and incoming sediment load from the hillslopes. The total sediment load can be categorised as suspended and bed loads based on the mechanism by which the grains move (Wilcock et al. 2009). Soil particles mechanically transported by suspension within the water flow are referred to as suspended sediment, whereas bed load consists of sediment particles that are moved along the bed of a stream by rolling, sliding or saltation (Turowski et al. 2010). A major portion of hillslope sediment load associated with soil erosion, widely known as wash load, remains continuously suspended unless there is a significant decrease in flow velocity and the particles of this load are finer than those along the river bed (Wilcock et al. 2009). On the other hand, a river carries sediment in the above-mentioned two distinct modes (Turowski et al. 2010). Estimation of suspended load is required in both hillslopes and channels for intensive water quality issues while bed load transport needs to be evaluated to maintain dynamically stable channel geometry (Barry et al. 2008). Sediment transport in a river basin includes suspended load transport, bed load transport and their interactive movements. A variable fraction of suspended loads transforms into the bed loads or, vice versa depending on particle size, flow discharge, shear stress, sediment concentration and transport capacity of flow. Thus, basin scale sediment budget estimation requires due consideration of the suspended loads, bed loads and their interactions.

A number of process-based soil erosion and sediment transport models at a watershed scale have been presented by different researchers over the past four decades (Bhattacharya et al. 2007) such as Soil and Water Assessment Tool (SWAT) (Neitsch et al. 2002), Sediment River Network model (SedNet) (Prosser et al. 2001a), SHETRAN (Ewen et al. 2000), European Soil Erosion Model (EUROSEM) (Morgan et al. 1993), Water Erosion Prediction Project (WEPP) (Nearing et al. 1989), Agricultural Nonpoint Source pollution model (AGNPS) (Young et al. 1987), Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) (Beasley et al. 1980) and Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel 1980). Most of these models incorporated process-based governing equations of only few processes explicitly and hence, their ability to simulate river basin sediment dynamics at a desired level is limited. For example, SWAT was developed for

the USDA-Agricultural Research Service (ARS) to assist water resources managers in predicting and assessing the impact of management on water, sediment and agricultural contaminants in large ungauged catchments (Borah and Bera 2003). The model used empirical approach (SCS curve number) for rainfall-runoff simulation. The amount of soil erosion was estimated using the conceptual Modified Universal Soil Loss Equation (MUSLE) (Bhattarai and Dutta 2008). Another model, SedNet was developed for estimating soil erosion and deposition in hillslopes, gullies and river networks (Merritt et al. 2003). The model simulates an average sediment load by using simple conceptual and empirical models of sediment detachment, transport and deposition. The model is not suitable for detailed sediment dynamics at channel networks in large-scale catchments. SHETRAN, a physically based and spatially distributed model, is an enhanced version of the SHE/SHESED model (Bathurst et al. 1995). The model simulates water, sediment and contaminant transport at the river basin scale by accounting surface and subsurface water interactions (Ewen et al. 2000). Whilst the model includes an option to simulate bed load and suspended sediment transport, there is no published peer-reviewed literature demonstrating the suitability of the model to simulate sediment budget in a large river basins. EUROSEM calculates sediment concentration and determines total soil loss, storm sediment graph after estimating total runoff and total storm hydrograph (Morgan et al. 1998). The model does not consider sediment dynamics in river systems separately. WEPP, introduced by US Department of Agriculture (Flanagan and Nearing 1995), is able to estimate hillslope soil erosion and sediment movement using process-based distributed hydrological modelling. The model consists of a stochastic weather model and is applicable only to small watersheds (Duna et al. 2009). The AGNPS model was developed at the USDA-ARS for simulating event based runoff, sediment and nutrient transport (Borah and Bera 2003). The model also uses rational formula for rainfall-runoff simulations and does not consider the channel sediment dynamics separately. The model estimates hillslope soil erosion by using Universal Soil Loss Equation (USLE). The AN-SWERS model, introduced by Beasley et al. (1980), is capable of simulating soil erosion and sediment transport through a process-based distributed modelling approach. The model calculates runoff using empirical relationships and is suitable for agricultural areas. The CREAMS model is an extended and modified version of GLEAMS, the Groundwater Loading Effects of Agricultural Management Systems (Connolly et al. 1999). The model uses simplified physics—based approaches to simulate water, sediment and pollutant transport (Merritt et al. 2003). The rainfall-runoff process in the CREAMS model is simulated using the SCS curve number approach while the erosion component maintains elements of the USLE (Merritt et al. 2003). In addition to this, some of the research undertaken with the above models was site specific. According to Bhattacharya et al. (2007), the prediction errors of most of the available soil erosion and sediment transport models are unacceptably high in many practical situations due to adoption of major assumptions and oversimplifications of an immensely complex naturally occurring sediment transport process.

Several sediment transport models were efficiently developed based on either single or separate transport equations for suspended and bed loads. For example, Spasojevic and Holly (1990) treated different sediment loads separately, while Armanini and Di Silvio (1988) and Wu (2004) simulated the suspended and bed loads by a single equation. Greimann et al. (2008) presented an equation for modelling suspended load, bed load, or mixed load depending on a transport mode parameter consisting of local flow hydraulics. Prosser et al. (2001b) presented a simple conceptualized model for detailed assessments of transport and deposition of suspended and bed loads in individual regional catchments. Turowski et al. (2010) reviewed the empirical data for suspended and bed load partitioning and presented an empirical equation to estimate

bed load transport rates from measured suspended load transport rates. However, none of these studies focused on catchment scale modelling of sediment loads and budgets.

The main aim of this study was to develop an approach for simulating suspended and bed loads and evaluating their interactions to estimate total sediment budget at a river basin scale. A process-based and distributed sediment dynamics (PBDS) model developed by the authors (Kabir et al. 2011a) was revised to incorporate a bed load simulation module for this study. Transport mechanisms of suspended and bed loads are distinctively different in nature (Turowski et al. 2010) and hence, these loads are modeled separately. The revised PBDS model was applied in the Abukuma River basin, a large basin in Japan (see Section 3), to evaluate the performance of the model and to explore the interactions between suspended and bed loads. The incorporation of the bed load simulation module in PBDS is the novelty of this research, which enables the model to estimate total sediment budget at a river basin scale. The paper introduces the revised PBDS model developed to estimate different sediment loads and their interactions and the sediment budget at a basin scale (see Section 2) and presents the outcomes of the case study application in the Abukuma River basin (see Section 4). The advantages and limitations of the model are discussed in Section 5 and the key conclusions are presented in Section 6.

2 Research Approach and Model Description

The flow chart of the overall modelling approach for basin scale sediment load analysis is shown in Fig. 1. A key assumption of the revised PBDS model is that only suspended sediments are generated and transported in hillslope areas whereas, rivers carry sediments in two distinct modes – as suspended and bed loads (Einstein 1950; Vanoni 1975; Turowski et al. 2010). Soil erosion is considered to be caused by the kinetic energy of the raindrops striking the soil surface both as direct rainfall and as leaf drip impact (Torri et al. 1987). Detachment of soil particles is calculated using suitable physical equations and the movement of suspended sediment is simulated using the principle of conservation of mass and momentum. It is assumed that the suspended sediment moves at the same velocity as the fluid. A transport capacity equation is used to set the limits of the suspended sediments that can be transported by the flow (Ferro 1998).

Sediment dynamics in channels differ from hillslope sediment processes and contribute significantly to watershed sediment budgeting (Ferro and Porto 2000) and as such, the requirement for modelling channel sediment processes separately has long been discussed (Atkinson 1995; Ferro and Porto 2000). Hence, the channel sediment dynamics are modelled separately in the revised PBDS model by incorporating the bed load estimation and transport in addition to the suspended load, which is mostly imported from the hillslopes. A bed-load transport equation is used to estimate the bed load amount. The bed load equation is based on instantaneous flow hydraulic parameters and it ignores the time rate change of the sediment concentration, since the bed load particles do not move in the same mode as the fluid. The exchange of sediment flux between the suspended and bed loads is incorporated in the estimation of the bed load. Hillslope soils and river bed materials are considered as the main source of the sediment particles of the suspended and bed loads, respectively. Particle size distribution of bed loads varies widely depending on the flow strength. Thus, dividing the bed load sediments into different particle size classes is an efficient approach to simulate the total bed load by

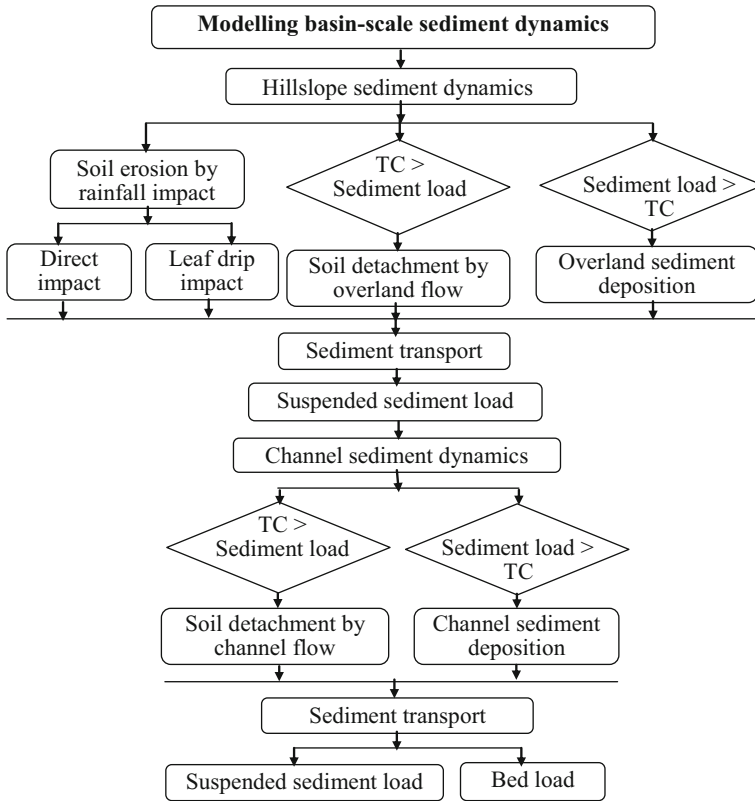


Fig. 1 A flowchart showing the key processes incorporated in the basin-scale process-based modelling approach and their interactions for analysing sediment loads and budgets

assuming the fraction of sediments in each class is similar to the respective bed material fraction. With this approach, the total bed load transport rate can be expressed as follows:

$$Total\ Bed\ Load = \sum_{k=1}^n P_k (Q_b)_k \tag{1}$$

Where,

- n Number of sediment particle size classes in riverbed materials.
- P_k Fraction of k -th sediment particle size class.
- $(Q_b)_k$ Bed load rate, by considering entire load consists of a single particle size class (k -th class) only.

Figure 2(a) shows a schematic diagram of this modelling concept and the key variables and parameters. The finite-difference solution schemes of the governing equations of the major processes used in the model are presented below discussed below. The definitions of all the symbols used in the equations are appended at the end of the paper.

Detachment of soil by rainfall in a hillslope grid is calculated using Eq. 2. The total Kinetic energy (KE) is calculated in Eq. (3) described in Kabir et al. (2011a).

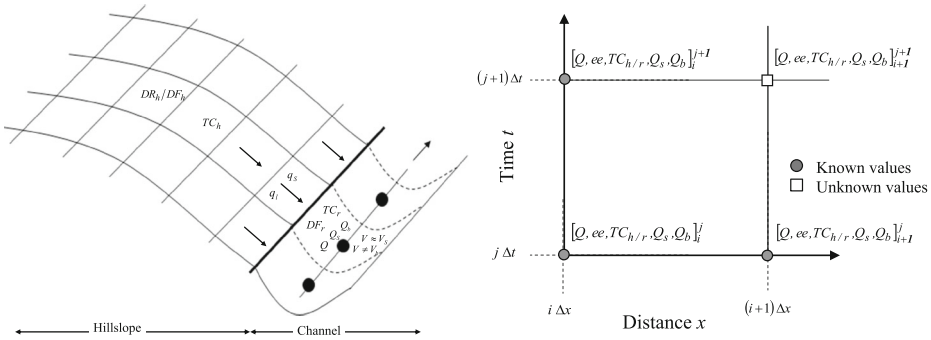


Fig. 2 **a** A schematic diagram of the basin-scale suspended and bed loads modelling by the process-based approach and **b** the space-time plane of the finite difference scheme used in the model along with the variables used in the space and time domains. Where, DR_h = Soil detachment by rainfall at hillslope area; DF_h = Soil detachment/deposition by overland flow; TC_h = Suspended sediment transport capacity concentration of overland flow; q_l = Lateral water discharge; q_s = Lateral suspended sediment flow; Q = Channel water discharge; TC_r = Suspended sediment transport capacity concentration of channel flow; DF_r = Soil detachment/deposition by channel flow; Q_s = Channel suspended sediment load; Q_b = Channel bed load

$$DR_{h_{i+1}}^{j+1} = \frac{k}{\rho_s} \left(KE_{i+1}^{j+1} \right) e^{-Z_{h_{i+1}}^{j+1}} \tag{2}$$

The model solves one-dimensional kinematic wave approximation of Saint–Venant’s principles (Chow 1965) to simulate water flow (Eq. 3) and suspended sediment transport (Eq. 4) in both hillslope grids and river nodes along the steepest descent direction. The kinematic wave equations are solved numerically using a backward finite-difference scheme. The concepts of overland and river flow simulations were adopted from the process-based hydrological model IISDHM (Dutta et al. 2000; Asokan and Dutta 2008; Dutta and Nakayama 2009).

$$Q_{i+1}^{j+1} = \left[\frac{\Delta t}{\Delta x} Q_i^{j+1} + \alpha\beta \left(\frac{Q_{i+1}^j + Q_i^{j+1}}{2} \right)^{\beta-1} Q_{i+1}^j + \Delta t \left(\frac{q_{l_{i+1}}^{j+1} + q_{l_{i+1}}^j}{2} \right) \right] / \left[\frac{\Delta t}{\Delta x} + \alpha\beta \left(\frac{Q_{i+1}^j + Q_i^{j+1}}{2} \right)^{\beta-1} \right] \tag{3}$$

$$(C_s)_{i+1}^{j+1} = \left[\Delta t \Delta x \left(ee_{i+1}^{j+1} + \frac{(q_s)_{i+1}^{j+1} + (q_s)_{i+1}^j}{2} \right) + \frac{\Delta x Q_{i+1}^j (C_s)_{i+1}^j}{V_{i+1}^j} + \Delta t Q_i^{j+1} (C_s)_{i+1}^{j+1} \right] / \left[\frac{\Delta x Q_{i+1}^{j+1}}{V_{i+1}^{j+1}} + \Delta t Q_{i+1}^{j+1} \right] \tag{4}$$

The transport capacity equation (Eq. 5) presented by Abrahams et al. (2001), which is found to be most suitable for the study area (Kabir et al. 2011b), is used to adjust the limit of suspended sediment amounts in overland and river flow. Soil detachments by flow and sediment deposition are mutually exclusive and considered to work simultaneously. This process is modelled using Eq. 6, which is based on particle settling velocity (Eq. 7).

$$(TC_{h/r})_{i+1}^{j+1} = \left[a d_{50} u_* Y \left(1 - \frac{Y_{cr}}{Y} \right)^{3.4} \left(\frac{V}{u_*} \right)^b \left(\frac{W_i}{u_*} \right)^c / q \right]_{i+1}^{j+1}$$

$$\text{Log}(a) = -0.42 * (C_r/D_r)^{0.2}; b = 1 + (C_r/D_r)^{0.2}; c = 0 \text{ if } w_i/U_* > 3, \text{ otherwise, } c = -0.5 \tag{5}$$

$$ee_{i+1}^{j+1} = [DF_{h/r} + DR_n]_{i+1}^{j+1} = [\beta_s \ wv_s (TC_{h/r} - C_{si})]_{i+1}^{j+1} + \frac{k}{\rho_s} (KE)e^{-Zh} \tag{6}$$

$$(v_s)_{i+1}^{j+1} = \left[\sqrt{13.95 \left(\frac{V}{d}\right)^2 + 1.09(G-1)g} \ d - 13.95 \frac{V}{d} \right]_{i+1}^{j+1} \tag{7}$$

The suspended sediment load is calculated using Eq. 8.

$$(Q_s)_{i+1}^{j+1} = (C_s)_{i+1}^{j+1} Q_{i+1}^{j+1} \tag{8}$$

A number of equations are available for bed load modelling that are mainly developed based on laboratory based experiments or using observed datasets, e.g., Ashida and Michiue (1972); Wu et al. (2000); Meyer-Peter and Müller (1948); Parker (1990); Wilcock and Crowe (2003). The performance of these equations varies depending on the site-specific characteristics. In this study, Ashida and Michiue (1972) equation (Eq. 9) was used to estimate the amount of bed loads, which is widely used in Japan. This equation uses a simplified particle equation of motion for evaluating dimensionless mean particle velocity in the bed load layer and is considered to be suitable for process-based hydrological modelling since the parameters used in the equation are largely associated with different hydraulic conditions commonly used in hydrological simulation (Garcia 2008; Kabir 2011; Kabir et al. 2012).

$$(Q_b)_{i+1}^{j+1} = \left[17 \ w \ P_k \sqrt{(G-1)gd_j^3} \ \tau_{*ej}^{3/2} \left(1 - \frac{u_{*cj}}{u_*}\right) \left(1 - \frac{\tau_{*cj}}{\tau_{*j}}\right) \right]_{i+1}^{j+1} \tag{9}$$

The total sediment budget is the sum of the suspended load (Q_s) and bed load (Q_b) (Eq. 10). The conditions used to define the interactions between Q_s and Q_b ; and the concept of estimation of total sediment load at any given time and space is shown in Eq. 11.

$$(Q_t)_{i+1}^{j+1} = (Q_s)_{i+1}^{j+1} + (Q_b)_{i+1}^{j+1} \tag{10}$$

$$\begin{aligned} &\text{If } ee_{i+1}^{j+1} > 0, \text{ then } ee_{i+1}^{j+1} (Q_s \text{ from } Q_b) \\ &\text{If } ee_{i+1}^{j+1} < 0, \left| ee_{i+1}^{j+1} \right| < (Q_b)_{i+1}^{j+1}, \text{ then } ee_{i+1}^{j+1} (Q_b \text{ from } Q_s) \\ &\text{If } ee_{i+1}^{j+1} < 0, \left| ee_{i+1}^{j+1} \right| > (Q_b)_{i+1}^{j+1}, \text{ then } (Q_b)_{i+1}^{j+1} (Q_b \text{ from } Q_s) \end{aligned} \tag{11}$$

3 Study Area and Model Setup

The model was applied in the Abukuma River basin, which is located in the northeast of Japan (Fig. 3a). It has an area of 5,400 km² and about 55 % of the basin is covered by forest area, which consists of mainly beech and oak forests. (Takeda et al. 2001; Oka et al. 2004) (Fig. 3b). The elevation of the basin ranges from the sea level to more than 2,000 m on the west side, to low elevation and gentle river slope in the east side. The basin, with an average slope of 7 %, has steep slopes within the range of 30 to 40 % in many places (Fig. 3c). Geological conditions

of the basin are characterized by the granite and the granodiorite extending on the east side and complex mixtures of the metamorphic rock, andesite and granite on the west side. Diluvium and alluvial soils are developed on the west side due to the erosion of volcanic products. Mean annual precipitation is as much as 1,500 mm on the west side, but less on the east side (1,200 mm) and the plain in the north area (1,100 mm) (Kinouchi and Musiaki 2008). With a length of 234 km, Abukuma is the sixth longest river in Japan. It originates from the Nasu Mountains in the Tohoku region, and ultimately drains into the Pacific Ocean (Takeda et al. 2001). The river network and the locations of the two gauging stations, Tateyama and Fukushima, used for the calibration and validation of the model, are shown in Fig. 3c. The average channel widths are about 450 and 275 m at Marumori and Fukushima, respectively.

The observed discharge at Fukushima and Marumori stations were used for calibration and validation of the hydrological module of the PBDS model as presented in Kabir et al., 2012. Observed time series of suspended sediment loads at Marumori station during two selected high flow events (in July 2002 and July 2004) were used for the calibration and validation of the suspended sediment load simulation module of the PBDS model, respectively. The entire catchment is divided into a set of uniform grids of 500-m resolution using GIS. The river network is also converted into a set of uniform grids of 500-m resolution and overlaid to the catchment grid network. All the grid cells located within the catchment boundary are modelled for streamflow and suspended sediment load using steepest slope direction except for the river grids. When a hillslope grid connects to a river grid in the direction of steepest slope, the simulated streamflow and suspended sediment load from the hillslope grid is added to the river grid to incorporate as lateral flux in the river routing. The temporal resolution of the simulation was 1 h.

4 Results

For the hydrological simulation, the model was calibrated against the observed streamflows by adjusting the Manning's roughness coefficients of different landcover types and the channel network. Soil detachability index (k), soil cohesion, particle sizes (d_{50}) and soil particle density (ρ_s) were used as the calibrating parameters for the suspended sediment modelling. After the final calibration, the average values of soil detachability index, soil cohesion and soil particle density for the basin were 1.8 g j^{-1} , 7.0 to 8.0 kPa and 2480 kg m^{-3} , respectively. The particle size classes were represented through d_{50} values (median of particle size), within the range

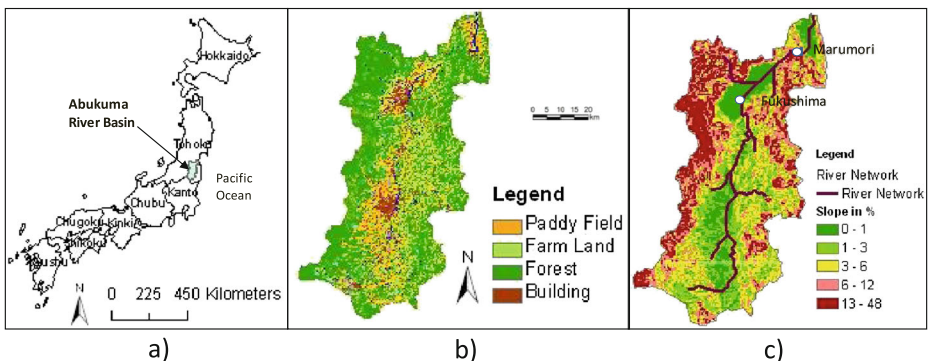


Fig. 3 a Location of Abukuma River basin in Japan, b Land use map, c Maps of slope and river network

from 25 to 45 μm . The detailed process of calibration and validation of the hydrological model and the results of that are already published by the authors (Kabir et al., 2011a). We have shown a comparison between the simulated and observed streamflow during the calibration and validation periods at Marumori station in Fig. 4(a and b) and summarized the results of the calibration and validation in Table 1 to demonstrate the performance of the model in the hydrological flux simulation. The model performed reasonably well in simulating streamflow at an hourly resolution during the periods of calibration (with $R^2 > 0.96$) and validation (with $R^2 > 0.87$). Figure 4(c and d) present the scatter plots of the simulated and observed suspended sediment fluxes during the periods of calibration and validation at Marumori. The simulated suspended sediment flux followed a trend similar to the observed data during the calibration (with $R^2 > 0.78$) and validation (with $R^2 > 0.82$). It is worth noting the exchange of sediment flux between the suspended and bed loads was computed at every time step of the simulation based on the respective sediment transport capacity at the nodes along the river network.

In Ashida and Michiue's equation, the bed load is primarily related to the flow depth and the slope of the channel. Since the range of the bed load particle sizes varies both temporally and spatially along a channel, d_{50} values were considered as the main calibrating parameter in the bed load modelling. The bed load along the main river channel was simulated by dividing the total loads into three different particle size classes. The percentage of the bed load in each class was assumed to be same as the percentage of sediment at the respective particle size class in the river bed material, which was derived from the particle size distribution at different gauging stations. Figure 5 shows the particle size distributions in Abukuma River bed at Marumori station as an example. The different particle size classes and their respective d_{50} percentages used in the simulation are presented in Table 2. The sediment density was considered to be $2,650 \text{ kg m}^{-3}$ in the bed load modelling.

The simulated bed load at Marumori during the flood events of July 2002 and July 2004 are presented in Fig. 6(a and b), respectively along with the observed suspended sediment load and water flow. The simulated bed loads seem to be reasonable and consistent with respect to the observed water flow. In absence of any observed bed load data during the modelling periods, the simulated bed load results were compared with the data obtained from a laboratory experiment. Figure 7 presents the simulated bed load with respect to the flow discharge for the two selected periods along with the data obtained from the laboratory experiment for the bed load measurement undertaken by Yorozuya et al. (2009) using Acoustic Doppler Current Profiler (ADCP) in Japan. Although the range of the simulated bed load does not match that of the experimental results, the extrapolated trend of the simulated bed load fluxes is consistent with the experimental results. The simulated bed load flux can be approximated with the water flow in a narrow range, which is similar to the results presented by other researchers (Barry et al. 2004 and Nord et al. 2009).

The relationship between the suspended and bed loads was analysed using the simulated results. As shown in Fig. 8(a and b), the suspended and bed loads exhibited a linear relationship during the two simulated flood events except during the highest discharges in the July 2002 flood. The suspended load increased substantially compared to the bed loads during that period (Fig. 8(a)), which was due to the increased sediment influx from the hillslopes. In addition, relatively more bed load particles converted into suspended load during the highest discharges. Figure 9(a and b) present the fractions of the suspended load and bed load over the total load, respectively, against the water flow during July 2002. The fraction of the suspended load increased with the increase of water flow (Fig. 9(a)), which was due to two main reasons: i) the increased amount of suspended sediments transported to the channels from the hillslope areas, and ii) relatively more bed load turned into suspended load due to the flow strength. However, the suspended sediment fraction decreased very slowly during the

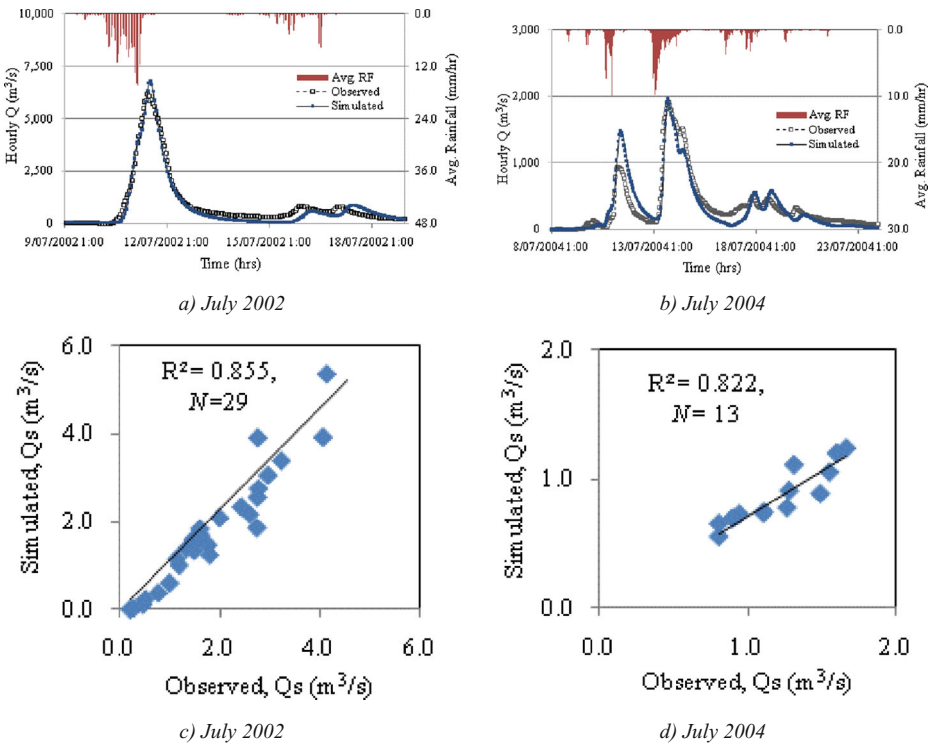


Fig. 4 The observed and simulated water discharge at Marumori station during: **a** calibration (July 2002) and **b** validation (July 2004) of the hydrological module of PBDSD model and Scatter plots of the simulated and observed suspended sediment discharge using Abraham’s transport capacity equation and the best fit lines for the periods of calibration (c) and validation (d) at Marumori

recession limb of the flood hydrography. On the other hand, a reverse trend was observed in case of the bed load fractions for the same flood event as shown in Fig. 9(b), since the total load is the summation of the suspended and bed loads. The bed load fraction as compared to the total sediment load was found to be around 0.6 to 0.8, which is similar to the figures presented in many past studies in Japanese rivers (Ashida and Okumura 1974; Ohmori 1991; Oguchi 1997).

The amount of sediment entrained from the bed load to the suspended load during the flood events of July 2002 and July 2004 are shown in Fig. 10(a and b), respectively. The results reveal that the suspended load increased significantly with more particles in suspension during the flood peak hours due to significant increase of flow strength at that periods. By contrast, some portion of the suspended load turned into bed load when the flow was substantially

Table 1 Performance evaluation of the model in streamflow simulation

Flood events	Items	Stations	No. of obs.	R ²
July 2002	Hourly, Q	Marumori	240	0.96
	Daily, Q	Fukushima	31	0.97
July 2004	Hourly, Q	Marumori	384	0.87

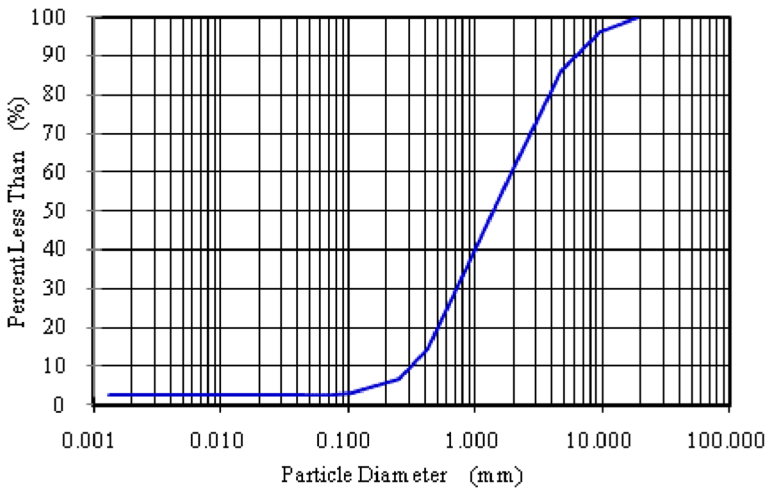


Fig. 5 Particle size distribution at Abukuma River Bed at Marumori

reduced at the end of the resession limb as shown in Fig. 10(c and d). The average rate of transfer of the bed load to the suspended load was significantly higher than the average transfer rate of the suspended load to the bed load during the two periods of simulation.

Table 3 summarizes the sediment budgeting at Marumori during the two flood events. The total suspended sediment load during the flood event of July 2002 was similar to the total bed load (with a ratio of 49:51). However, the total suspended load was less than half of the total bed load during the flood event of July 2004. This was due to the differences in the magnitudes of the water discharge during the two events. Higher water discharge during the peak of the July 2002 flood generated significantly larger amount of the suspended load. Relatively smaller flood event of July 2004 produced less amount of the suspended load as well as the total sediment load.

5 Discussion

One of the key components of basin scale sediment budgetting is the estimation of suspended sediment load from the hillslopes and along the channel network. The estimation of suspended load is highly sensitive to the method used to determine the transport capacity of the water flow. Different transport capacity equations were used in various studies (Yalin 1963; Bagnold 1980; Low 1989; Govers 1990; Everaert 1991; Jayawardena and Bhuiyan 1999; Abrahams et al. 2001) and not all equations are equally applicable to a particular river basin. The transport

Table 2 Particle size classes used in the bed load transport simulation in the main channel in Abukuma River basin

Particle size class	Average d_{50} values	Percentage of this size class presents in channel bed materials
0.3 to 0.9 mm	0.60 mm	≈ 29 %
0.9 to 2.00 mm	1.20 mm	≈ 34 %
2.00 mm and above	2.50 mm	≈ 37 %

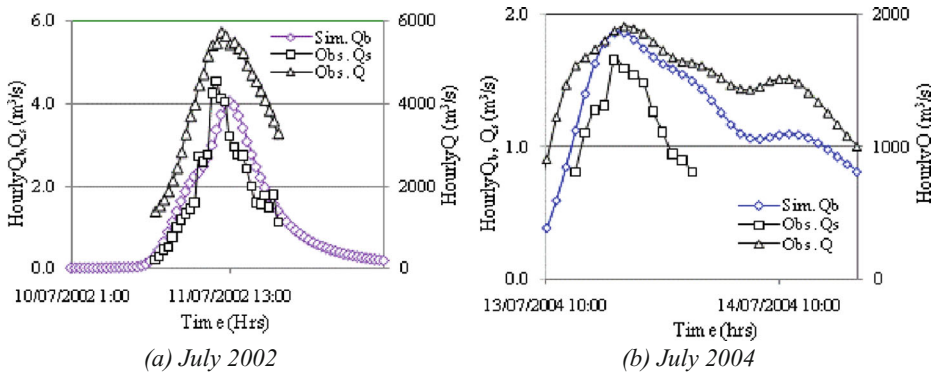


Fig. 6 Simulated bed load (Q_b), observed suspended sediment load (Q_s) and the observed water flow (Q) at Marumori during the flood events of July 2002 (a) and July 2004 (b)

capacity equation by Abrahams et al. (2001) was used in the model for this study after a through review and sensitivity analysis undertaken in the Abukuma basin with seven widely used transport capacity equations (Kabir et al. 2011b).

Similarly, a number of equations are available for bed load modelling (Ashida and Michiue 1972; Wu et al. 2000; Meyer-Peter and Müller 1948; Parker 1990; Wilcock and Crowe 2003). In this study, the Ashida-Mitsui equation was used due to its suitability in Japanese river basins and is considered to be suitable for process-based hydrological modelling since the parameters used in the equation are largely associated with different hydraulic conditions commonly used in hydrological simulation. For other hydro-geo-climatic regions, evaluation of different bed load equations should be undertaken.

The computational time of the model was reasonable, it took less than a hour in a standalone desktop computer to run the model in the Abukuma basin at a daily time step for the two flood events. The model was run multiple times for the calibration.

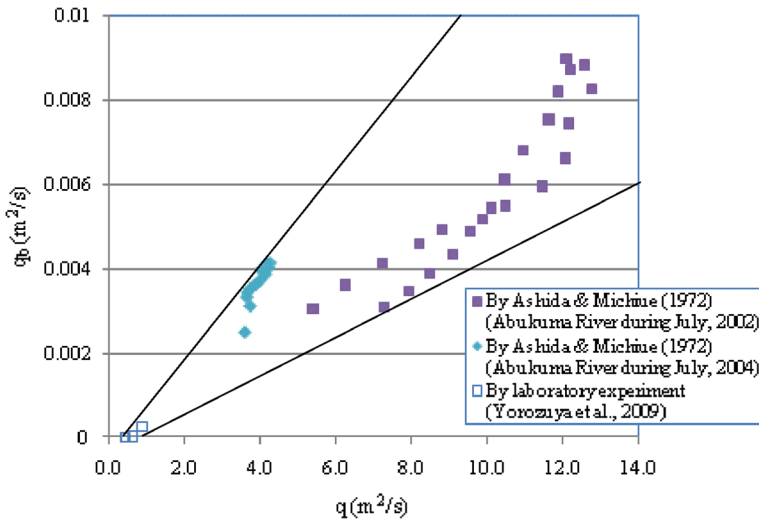


Fig. 7 Scatter plot of the simulated bed load versus the observed water discharge rate along with the measured bed load from a laboratory experimental undertaken by Yorozuya et al. (2009)

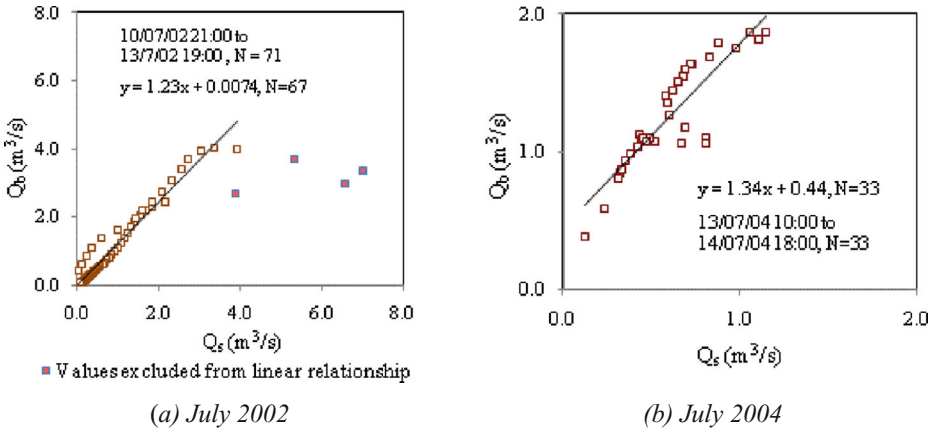


Fig. 8 The simulated bed loads as a function of the suspended loads at Marumori for the flood events of July 2002 (a) and July 2004 (b). In Fig. 9(a), the highest discharge values were excluded from the linear relationship fitted between the suspended and bed loads

In this study, the erosion in a river represented the erosion of the bed of the river only, the river bank erosion was not modelled. That did not have much influence on the results of the case study application in the Abukuma basin as bank erosion was very limited in the Abukuma River. It is recommended to incorporate bank erosion in such modelling in other river basins, where river bank erosion is a major factor contributing to the suspended load, bed load and total channel erosion.

Process-based distributed modelling of sediment dynamics is data intensive. Observed water quality data (in particular bed load data) are very sparse in most of the river basins around the world (Dutta et al., 1998; Alam and Dutta, 2013). We have best utilised the available data (that were accessible to us) for evaluating the model in the Abukuma basin. In further application of the model in other hydro-geo-climatic regions, it is recommended the model is tested against high quality observed data for different flow events of longer duration.

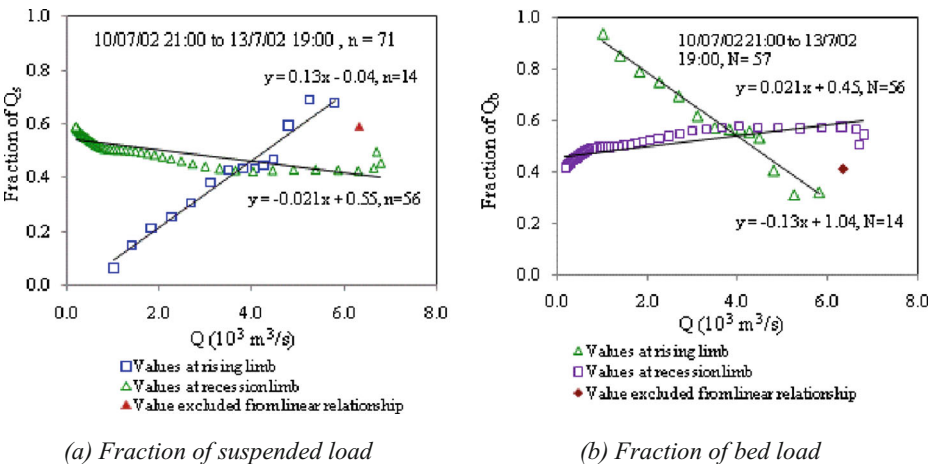


Fig. 9 Fraction of the suspended sediment over the total load (a) and the bed load over the total load (b) with respect to the observed water flow at Marumori during July 2002 flood

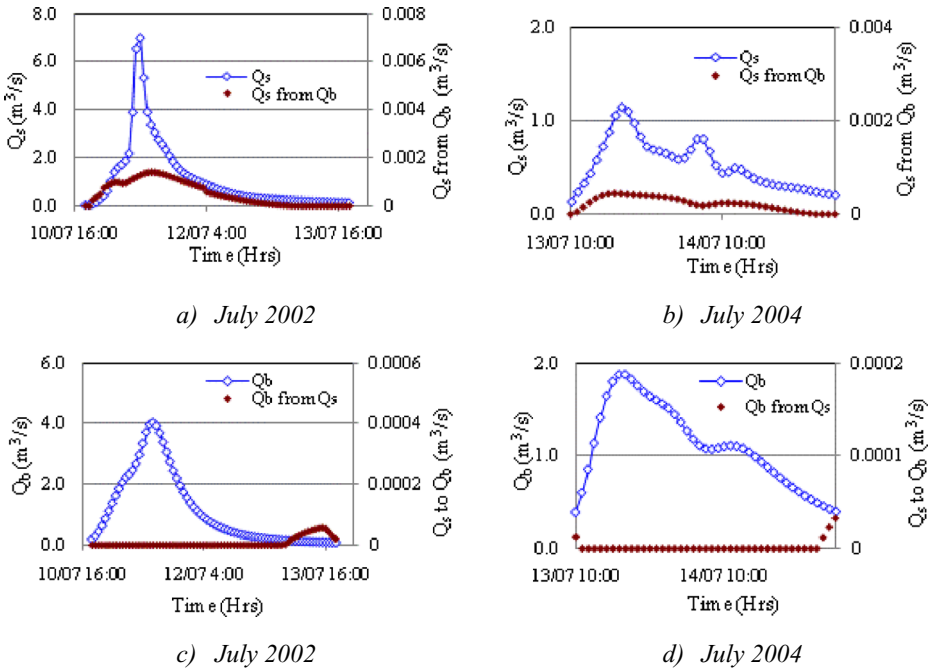


Fig. 10 Fraction of the bed load turns into suspended load during the flood events of July 2002 (a) and July 2004 (b) and fraction of the suspended load turns into the bed load during the flood events of July 2002 (c) and July 2004 (d) at Marumori

6 Conclusions

The paper presented a process-based distributed modelling approach for evaluating interactions between suspended and bed loads and for sediment budgeting at a river basin scale. In this approach, hillslopes and channels are modelled separately, and it is assumed that in the hillslopes runoff transports sediment in a single mode i.e., suspended sediment transport whereas, streamflow carries sediment in two distinct modes, suspended sediment transport and bed load transport. Suspended sediment transport was modelled using one-dimensional kinematic wave approximation of Saint-Venant’ principles of conservation of mass and momentum. Abrahams transport capacity equation was used to define the limit of sediments to be transported as suspended sediment. Bed load was simulated using Ashida and Michue’s bed load transport equation. The model was applied in the Abukuma River basin, Japan to evaluate its performance using the data from two recent flood events of 2002 and 2004.

Table 3 Sediment budgets, suspended and bed loads at Marumori station during the flood events of July 2002 and July 2004(ML = Mega litre)

Period of analysis	Suspended load (Q _s , ML)	Bed load (Q _b , ML)	Total sediment budget (Q _s +Q _b , ML)
July 2002 (10/07/2002 19:00 to 13/07/2002 19:00)	20166.95	21014.60	41181.55
July 2004 (13/07/2004 10:00 to 15/07/2004 4:00)	3443.53	7128.89	10572.42

The model has satisfactorily simulated the suspended sediment during the same periods with the R^2 values of 0.78 and 0.82 at Marumori. The simulated bed load was found to be reasonable and consistent with the water flow and it showed a similar trend with the experiment data. Based on the simulated results, an analysis of interactions between suspended and bed loads was carried out for the two flood periods. The results show the bed load can be expressed as a linear function of the suspended load. The fractions of different sediment loads with water discharge can also be expressed via simplified linear relationships by presenting sediment dynamics at the rising and recession limbs separately. The flood event with higher intensity streamflow produced significantly larger amount of suspended sediment and had higher interaction with the bed loads.

The case study application has demonstrated that the approach can effectively describe the basin scale sediment budgets with due consideration of the suspended load in the hillslopes and suspended and bed loads and their interactions in the channels. It allows a critical evaluation of interactions between suspended and bed loads in waterways for many applications.

7 Notation

A list of symbols used in this paper.

Symbol	Meaning (unit)
β_s	Correction factor for cohesive soil erosion (-)
ρ_s	Soil particle density (kg m^{-3})
$\Delta x, \Delta t$	Spatial, temporal intervals (meter, sec)
τ	Shear stress (kPa)
τ_{*j}	Nondimensional Shields stress associated with j -th grain size (-)
τ_{*ej}	Nondimensional effective stress associated with j -th grain size (-)
τ_{*cj}	Nondimensional critical Shields stress associated with j -th grain size (-)
ν	Kinematic viscosity of water ($\text{m}^2 \text{s}^{-1}$)
a, b, c	Coefficients relate to sediment transport capacity (-)
c_r	Stone cover (-)
C_s	Suspended sediment concentration ($\text{m}^3 \text{m}^{-3}$)
C_{si}	Initial suspended sediment concentration ($\text{m}^3 \text{m}^{-3}$)
d	Particle diameter (meter)
d_{50}	Median grain size (μm)
D_r	Stone Size (-)
$DF_{h/r}$	Flow detachment or deposition ($\text{m}^3 \text{s}^{-1} \text{m}^{-1}$) Subscript 'h' for hillslope flow and 'r' for river flow
DR_h	Soil detachment by rainfall at hillslope area ($\text{m}^3 \text{s}^{-1} \text{m}^{-1}$)
ee	Flow detachment (+ve)/deposition (-ve) ($\text{m}^3 \text{s}^{-1} \text{m}^{-1}$)
h	Depth of water (meter)
KE	Kinetic energy (J g^{-1})
g	Acceleration due to gravity (m s^{-2})
G	Specific gravity of soil (-)
i, j	Spatial, temporal points (-)
k	Soil detachability index (g j^{-1})

N	No. of observations (–)
P_k	Fraction of k -th sediment particle size class in river bed materials (–)
q	Water flow per unit width ($\text{m}^2 \text{s}^{-1}$)
q_l	Lateral water flow per unit width from surface to river ($\text{m}^2 \text{s}^{-1}$)
q_s	Lateral suspended sediment flow ($\text{m}^2 \text{s}^{-1}$)
Q	Water flow ($\text{m}^3 \text{s}^{-1}$)
$Q_{s/b}$	Sediment flow ($\text{m}^3 \text{s}^{-1}$)
	Subscript ‘s’ for suspended load and ‘b’ for bed-load
$(Q_b)_k$	Bed load for k -th sediment particle size class ($\text{m}^3 \text{s}^{-1}$)
s	Slope gradient (–)
$TC_{h/r}$	Transport capacity concentration ($\text{m}^3 \text{m}^{-3}$)
	Subscript ‘h’ for hillslope flow and ‘r’ for river flow
u_*	Shear velocity (m s^{-1})
V	Flow velocity (m s^{-1})
V_s	Velocity of suspended sediment particles (m s^{-1})
V_b	Velocity of bed-load particles (m s^{-1})
v_s	Particle settling velocity (m s^{-1})
w	Water flow width (meter)
w_i	Inertial fall velocity (m s^{-1})
x, t	Distance, time (meter, sec)
Y, Y_{cr}	Shields parameter (–)
Z	Soil texture index (–)

Acknowledgments This project is funded by NEWJEC Inc., Japan and the small grant scheme of Monash University Gippsland Campus. The data for modelling in the Abukuma Basin was provided by NEWJEC Inc.

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